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13. ABSTRACT (Maximum 200 words)

The scope of this work is to study the possibility of utilizing devices operating at 0.3THz-30THz for telecommunication applications in general and for interconnects within the box, in particular, for example for Smart Antenna Driver-Receiver-Switch System for Wireless Communication. Our approach in the period covered by this report has been to organize brainstorming sessions within our group to develop potential application areas that could take advantage of interfacing optical interconnects with THz devices within the context of the scope of the program. To this date we have come up with two novel concepts: one to utilize 30THz optical sources for point to point free space optical communication and the second to use two-coupled cavity VCSEL structure for THz modulation. We have also pursued the analysis of a Smart antenna driver for wireless communication to derive the potential benefits of optical interconnects for this application.

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I. Scope of the work:

The scope of our proposed work was to study the possibility of utilizing devices operating at 0.3THz-30THz for communication applications in general and in particular for interconnects within the box to be used in space, for example for Smart Antenna Driver-Receiver-Switch System for Wireless Communication.

II. Approach and key results:

Our approach during the study period has been to organize brainstorming sessions and carry out literature surveys and perform very preliminary system design studies to assess the level of maturity of the field for supporting systems level research and to develop potential application areas that could take advantage of THz devices within the context of the scope of the program. Because of the recent developments in the field of quantum cascade lasers[1] that are compact and can potentially be manufactured in large quantity and can address the 5-70μm region of the electromagnetic spectrum during the latest part of the program we concentrated our efforts in areas that could benefit from these lasers.

One potential application area that we have explored early on in the program was to utilize 30THz (10μm) optical sources (quantum cascade lasers) for point to point free space optical communication. We believe this application has significant merit and we have established a research collaboration with a local San Diego based Company, Maxima that is developing the necessary technologies in collaboration with Alp Inc. from Switzerland to address the point to point access market for the last mile.

The second application area we have considered is that of interconnects in the box for satellite applications. Specifically, we have considered a Smart Antenna Driver for wireless communication. Our discussions indicated that at this time conventional optical interconnects are best suited for this application and the THz technology is yet immature for becoming a serious technology alternative and/or to complement electrical or optical interconnects. We feel that this conclusion results from the fact that we have considered a system application that is too near term and that does not rely on the inherent properties of THz radiation.

We now believe that THz radiation based communication is advantages at this point in time (and for the foreseeable future until the cost of THz components can be lowered significantly) only for systems where THz radiation performs a task that cannot be accomplished by other more conventional means. We have therefore turned our attention to THz sensing, spectroscopy and imaging[2]. Several experiments performed by the biological research community have shown that THz imaging and spectroscopy can lead to the sensing of valuable additional information for example when studying biological tissue. However, in in order to build a competitive THz imaging system practical and efficient means to transport THz radiation (e.g., waveguides) to desired locations are not yet available. In addition the signal to noise ratio and the resolution and parallelism of available detectors are simply not sufficient. We believe that the recent demonstrations of guiding THz radiation in dielectric waveguides suggest that THz guided interconnects can significantly enhance the practicality of THz imaging and perhaps enable in vivo imaging of biological tissue opening up significant commercial applications. Indeed the compatibility of THz radiation with plastic waveguides can be important in various sensing applications especially if plastic waveguide bundles could be engineered for carrying images at THZ radiation.

III. Background:

As shown in Fig.1, terahertz radiation spectrum (3mm to 15μm) lies on the boundary of electronics (mm-wave) and photonics (far-infrared). In this region of the spectrum, the absorption by polar water molecules makes the atmosphere totally opaque. Thus for free-space telecommunication, the terahertz radiation spectrum is limited to space applications such as satellite communication, or very short distance communication for example for within the box applications and/or for applications requiring sensing or imaging such as detection of polar gases like pollution control or terahertz spectroscopy. Unfortunately, in the past, and even today the complexity and rarity of THz radiation sources also limit the usefulness of this spectral region. Radiative sources at the THz spectrum are rare, complex and expensive. Since the success of any commercial system is cost sensitive, it is important to develop concepts for low cost, reliable and compact THz radiation sources.

For the far infrared optical window, where the atmosphere is highly transmissive, devices generating 20-40THz (8-15μm) radiation can be used for atmospheric telecommunication applications including earth to satellite communication and may present even a commercial opportunity with applicability to point to point local access networks for the last mile.

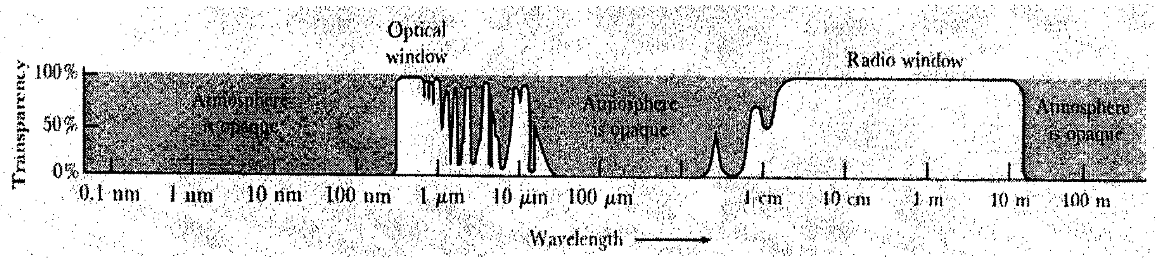

Figure 1: Transmission spectrum of atmosphere

IV. Key Findings:

Based on the above arguments we have focused our attention to three areas

1) 30 THz radiation for access networks

Since radiation at 8-11μm window is not affected by water molecules, it is possible to use this wavelength range for free space telecommunication [3]Military applications and earth to satellite communication applications have already taken advantage of the CO_2 lasers that operate at 10.6μm wavelength. However, these lasers are bulky, difficult to modulate at high speed and relatively expensive. The recently developed semiconductor quantum cascade (QC) lasers however, are capable of addressing this spectral window and we believe open the possibility of using effectively free-space optical communication to address the last mile problem. Recently several companies have spun off (e.g, Air Fiber, Light Point etc…) to solve the last mile problem of access networks using free-space optical communication. In contrast to fiber optical telecommunications, this technique has the advantage of not requiring additional cables to be buried in the ground. In old urban areas where fiber optical do not exist, fast free-space optical data links will be particularly convenient. The aim of these companies is to provide easily deployed networks that bring high bandwidth connections to the home. Presently, these companies plan to leverage on 850nm and 1.55nm lasers developed for fiber optics to realize point to point connections in free-space.

Some of the challenges in designing free-space optical networks are

- compensating for the effects of atmospheric turbulence resulting from temperature variations,
- background radiation due to sunlight,
- optical power limitations due to eye safety considerations(at certain wavelengths).

Over the last few years solutions have emerged for these challenges. However, one important challenge has not been addressed and that is the sensitivity of this type of network operation to fog conditions. Because fog particles are typically in the 0.5 to 2μm in diameter radiation in the near IR wavelengths is strongly scattered by fog. By using the 8-11μm window, where the wavelength of light is significantly larger than the fog particle size this limitation of free space optical access networks can be removed while helping in improving their performance in terms of atmospheric turbulence and eye safety issues. Thus we believe that the quantum cascade lasers originally developed at Lucent and now commercially available by several vendors (Alp in Switzerland) can become an important THz radiation source for solving the last mile problem. This type of networks is also important for military mobile communication systems.

Recently developed QC lasers are very suitable for such applications because their emission wavelength can be in the atmospheric window, and the fast internal lifetimes of the devices should allow for reasonable modulation frequencies of up to 5-l0GHz. Recently, Martini *et at.* published results of an optical data link using a high-speed modulated, liquid nitrogen-cooled QC laser over a distance of 10m and under laboratory conditions[4]. But this experiment was carried out within a building, and did not address one of the main benefits of using QC lasers, namely having an emission wavelength which is barely affected by atmospheric conditions such as fog. We have collaborated with Maxima researcher in the design of an experiment to use a QC laser manufactured by Alp to demonstrate a free space optical link that worked in real world conditions. The optical data link was more than 500m and used a Peltier-cooled QC laser and a roomtemperature HgCdTe detector. Initial experiments indeed show that the communication link was not perturbed by fog.

2) Study of concept for a new optical device for THz modulation

As discussed earlier, one of the most significant drawbacks of the THz spectrum is the lack of low cost modulation source. We believe that if low cost compact THz modulation sources were available, applications such as spectroscopy on bio-chips and in box interconnects that rely on free-space optics would become more attractive.

To come up with potential concepts for such a THz modulator, we held two brainstorming sessions at the onset of this program within our research group. A rather far out yet promising concept had emerged from our discussion. At Sandia, K. Choquette and co-workers [Fisher et.al., Appl. Phys. Lett., 75 p.3020, 1999], have described a coupled-cavity vertical cavity surface emitting laser. Our thinking was that it should be possible using this structure to obtain a THz modulated optical radiation with a carrier frequency around 350THz (850nm). In such a coupled cavity device the THz radiation can originate from the beating of the modes corresponding to each cavity. Unfortunately our initial feasibility studies demonstrated that such a laser would be unstable even for slight changes in temperature and very difficult to operate in a reliable manner. We believe that QC lasers that have been very recently reported[1] for 67μm radiation are more promising and manufacturable. We therefore abandoned this direction.

3) In-box Communication

With the advent of QC lasers as a potential compact source for THz radiation, it became relevant to investigate whether this type of laser can also make an impact in shorter distance communication systems. To this end we have chosen two application areas: Smart antenna driver and switch boxes to be housed in satellites for wireless communication, and interconnects for a THz biological imaging system.

a. *Smart Antenna Driver and Switch:*

Wireless communication networks that are presently deployed relay data through a satellite link or a relay terminal to a central base-station. The former allows the data to skip over congested network nodes but has low bandwidth capabilities, high power requirements and long latency periods. The latter can support high-bandwidth data transfer, but as mobility increases, the performance of the link can degrade over an order of magnitude due to interference, channel fading and environmental factors. In addition, the single base-station does not scale well in bursty traffic scenarios.

Improving the switching speed of the link is key to improve on these limitations, such that additional upstream processing can be brought to bear upon the signal. Another method to combat interference at higher frequencies is to install several relay cells close to the transmission sources. By decreasing the transmission distance between the mobile terminal and the wireless network edge, BER (bit-error rate) and QoS (quality of service) is improved. However, at some point there is a capacity limit reached not due to a switching speed limitation, but based on the fact that the ICs that perform the signal processing cannot communicate with each other fast enough.

To meet the capacity need, the industry trend is to provide a solution in base stations that serve smaller regions, called micro- and pico-cells. One important component in future deployment of pico-cells is the usage of smart antennas. Smart antennas are comprised of multiple elements, each element phase-delayed with respect to each other. This allows beam-forming to occur. A major benefit of smart antennas is that they can improve system capacity. This occurs in two ways. If the subscriber and base station operates in the same range as a conventional system, but at a lower power, this may allow FDMA and TDMA systems to be re-channeled to reuse the frequency channel more often than in systems using conventional fixed antennas, since the carrier-to-interference ratio is much greater when smart antennas are used. In CDMA systems, if less power is transmitted for each link, then multiple access interference is reduced, which increases the number of simultaneous subscribers that can be supported in each cell. Second, smart antennas can also be used to spatially separate signals, allowing different subscribers to share the same spectral resources, provided each is spatially-separable at the base station. This technique, called Space Division Multiple Access (SDMA), allows multiple users to operate in the same cell, on the same code/frequency/time slot provided, using the smart antenna to separate the signals, leading to increased capacity within a limited spectrum allocation.

However, such benefits come at the cost of increased complexity, namely the processing involved in spatially separating multiple signals over an entire array. This leads to a limitation on the number of antenna elements usually to four to eight elements. Additionally, decreasing the signal frequency to support slower processing with more elements means that antenna array size becomes larger, creating a larger 'footprint' for the entire system, as well as a decreased data rate per channel.

To find a practical solution to this limitation, we have been examining the potential benefits of using non electrical interconnects. One possibility is to use WDM by directly interfacing the antenna array to the optical layer for direct millimeter-wave signal processing via modulation of a DFB laser. Modulation of the laser cavity produces temporal outputs at different wavelengths, which are then diverted via a Bragg grating into different channels enabling optically distributed processing to be performed. Lately optical approaches have been gaining acceptance for this type of applications.

Once the processing is completed, the n output signal can be multiplexed optically. For creating a relative phase delay between antenna elements, the output signal will be converted to base band where the phase delay for each element will occur and then up converted to the transmission frequency.

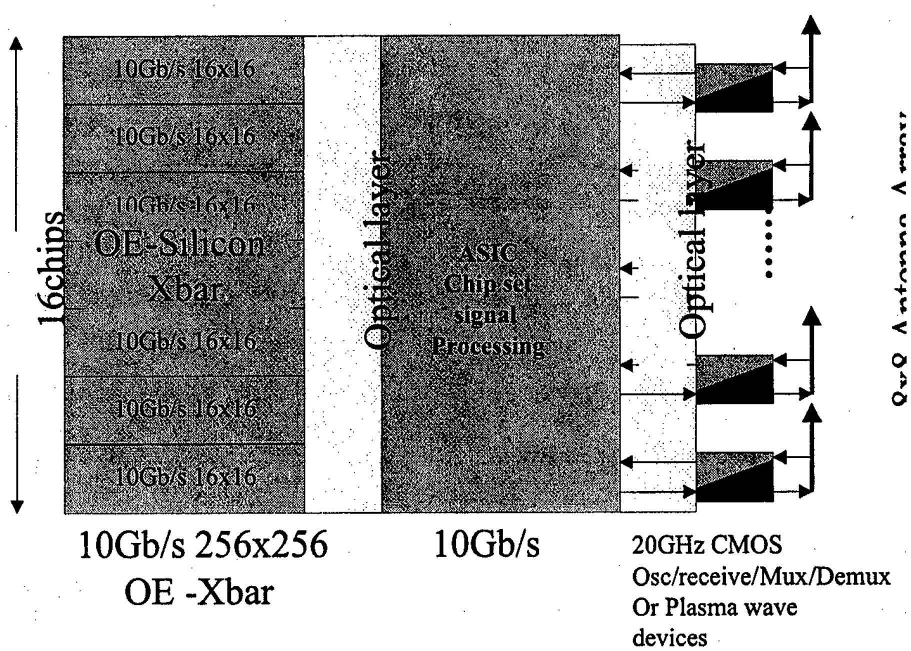

Figure 2. Schematic of a Smart antenna driver receiver switch system.

Requirements for in box interconnects for Smart Antenna driver-switch applications:

To select the proper interconnect technology for the above described application area the following requirements can be derived

***Modulation Speed*:** Typically for Smart Antenna applications the system performance requirements can be translated to 10-40Gb/s bit rates with 10^{-9} or better BER for interconnection lengths up to 1m.

***Number of Channel*:** Typically 64 channels are required but the number of channels must be scaleable and channel densities must exceed 16 channels/mm2.

Transport medium: low loss transport in flexible guides or in free space is critical. Typically more than 3dB loss is unacceptable.

***Reliability*:** The most critical aspect for space applications is reliability. For example even at this advanced manufacturing stage the reliability of NIR VCSELs cannot satisfy the reliability for interconnects to be used in computing and space applications. On the other hand the reliability physics of QC lasers is significantly different and it is worth as a further study to investigate their defect mechanisms.

As is clear from the above requirements both light sources and detectors in the 3-30THz region do not possess the necessary requirements for such applications in terms of modulation speed and the SNR required. In addition due to their longer wavelength the density of interconnects that could be achieved with Terahertz radiation would be much less than its optical counterparts.

b. Interconnects for in vivo THz imaging system

The field of terahertz imaging is a non-invasive method to obtain the composition of various objects. Molecules have dense and distinctive absorption spectra in the far infrared, enabling terahertz spectroscopy to provide distinct signatures for various materials[5],[6]. Terahertz radiation can penetrate non-polar substances such as fats, cardboard, cloth and plastic with little attenuation. However, Terahertz radiation interacts strongly with polar molecules, an important example being water. Water molecules absorb terahertz waves limiting penetration of the radiation to a millimeter or so in most biological substances which are typically more than 95% water. Typically a coherent detection method is used, whereby both amplitude and phase of the terahertz beam are measured, providing an exact terahertz signature of the material under observation. In principle, it is possible to calculate the absorption and refractive index spectra of a transmitted or reflected pulse and thus determine the molecules that are present in the terahertz beam path. In practice, the attenuation is often too severe for a signal to be transmitted; that is only thin samples or surface molecules can be analyzed. Although this is acceptable in laboratory conditions to carry on scientific experiments a much larger market could be opened up if THz radiation could be used in vivo by relaying via endoscope like guides the radiation to areas of interest.

V. Conclusions:

In designing systems that use electromagnetic waves for information sensing, transport, or processing, it is critical to have access to efficient sources and detectors, and means of transporting and modulating the radiation. Based on our studies and attempts to design on paper preliminary systems we feel that THz engineering has come a long way over the last two years mostly because of the potential promise of QC lasers both as reliable and compact radiation sources but also as fast modulators. We should however point out that the L-I curve efficiency and threshold currents of QC lasers must still be significantly improved (10X for threshold) before they can be used in real world systems. It is also possible that similar physics and techniques that were used to demonstrate THz QC lasers can be adopted for THz radiation detection. This is important because ultimately it is the detector that dictates the performance of an electromagnetic system and presently THz detectors are far from being acceptable both in terms of speed and sensitivity. Under certain condition free space propagation can provide adequate means for transport. However, it appears that systems level research could strongly benefit from the development of flexible THz waveguides for transport. There is recently good evidence that plastic waveguides could be designed and used to transport THz radiation with low loss[7]. This appears to be an important direction that certainly deserves further investigation.

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